Submitted to the Astrophysical Journal
Preprint typeset using LaTeX style emulateapj v. 11/12/01

THE VARIABILITY OF GAMMA-RAY BURSTS THAT CREATE AFTERGLOWS

Joseph A. Muñoz[1] and Jonathan C. Tan[1,2]
1. Princeton University Observatory, Peyton Hall, Princeton, NJ 08544, USA
2. Inst. of Astronomy, Dept. of Physics, ETH Zürich, Hönggerberg, 8093 Zürich, Switzerland
jmunoz@princeton.edu, jt@astro.princeton.edu
Submitted to the Astrophysical Journal

ABSTRACT

We consider whether the variability properties of Gamma-Ray Bursts (GRBs) that produce bright optical and longer wavelength transient afterglows (A-GRBs) are the same as a larger, inclusive sample of bright, long-duration GRBs, selected only by their γ-ray emission. This sample may include a significant population of physically distinct "dark" or "faint-afterglow" GRBs with different variability properties, or may be composed of a single population, some of which lack afterglows only because of observational selection effects. We argue that the structure function is the most appropriate method for measuring the variability of bursts because of their transient and aperiodic nature. We define a simple statistic: the ratio of the integrated structure function from 0.1 to 1 s compared to that from 0.1 to 10 s, as measured in the observer frame. To avoid instrumental effects we restrict our analysis to GRBs with BATSE data. Comparing 10 A-GRBs to a "main" sample of about 500 bursts, we find there is a probability of only 0.03 of the samples being drawn from the same population, with the A-GRBs tending to have relatively less power on sub-second timescales. We conclude that this result is tentative evidence for variations in the properties of GRB progenitors that affect both the gamma-ray and afterglow properties of long-duration GRBs. In addition, our method of analyzing variability identifies a characteristic timescale of ~ 1 s, below which variability is suppressed, and finds a trend of increased short timescale variability at higher γ-ray energies. The long-duration GRBs that we identify as having the most sub-second timescale variability, may be relatively bright examples of short-duration GRBs.

Subject headings: gamma rays: bursts

1. INTRODUCTION

The origin of Gamma-Ray Bursts (GRBs) continues to be a challenging problem. Observationally there is now clear evidence linking *some* long-duration GRBs with the deaths of massive stars in explosions known as supernovae or hypernovae. GRB 980425 was likely associated with SN 1998bw (Galama et al. 1998), while the connection of GRB 030329 with SN 2003dh is even more convincing (Stanek et al. 2003). There is also tentative evidence associating GRBs that produce longer-wavelength transient afterglows (A-GRBs) with galactic star-forming regions (Kulkarni et al. 2000; Djorgovski et al. 2001; Bloom et al. 2002; Frail et al. 2002; Djorgovski et al. 2003).

The observed nonthermal γ-ray spectra of GRBs and their short variability timescales necessitate relativistic motion of the material producing the photons (Fenimore et al. 1993; Woods & Loeb 1995; Tan, Matzner & McKee 2001; Lithwick & Sari 2001). The deceleration of this ejecta by the surrounding medium is then thought to produce the observed longer-wavelength afterglows.

Creation of relativistic ejecta from massive stars is a major theoretical challenge because of the complicated physics involved in supernova explosions and the uncertain initial conditions - i.e. the stellar structure just before core collapse. Overcoming the "baryon-loading problem" in these scenarios is an acute problem. If the relativistic ejecta producing the GRB acquire their high velocity close to the forming black hole, then this engine must operate for a time long enough for the outflow to first pierce and clear a path through the stellar envelope (e.g. Aloy et al. 2000; Proga et al. 2003; Zhang et al. 2003; Matzner 2003). This is many dynamical timescales of the inner black hole accretion disk. Alternatively, the ejecta that eventually produce γ-rays may be accelerated to relativistic speeds as the supernova explosion breaks out of the star (Colgate 1974; Matzner & McKee 1999; Tan et al. 2001). This last process inevitably occurs at some level in central, energetic explosions of stars.

The spectral and temporal properties of GRBs and their afterglows produced in these scenarios may be quite distinct. In the first model (i.e. involving production of ultra-relativistic ejecta near the forming black hole) γ-rays are likely to be produced predominantly from internal shocks in the jet or outflow, and the variability may reflect timescales associated with the inner accretion disk around the black hole or the hydrodynamic instabilities associated with the interaction of the outflow with the stellar envelope. In the second model (i.e. where the ejecta only become ultra-relativistic far from the central engine, beyond the radius of the pre-supernova star) γ-ray emission probably comes from an external shock and variability will be on longer timescales, perhaps associated with inhomogeneities in the external medium (e.g. Dermer & Mitman 1999). Such models have been criticized because it is difficult for them to efficiently produce GRBs with very short timescale variability (e.g. Piran 1999). Also Ramirez-Ruiz & Fenimore (2000) pointed out that there was no evidence that individual pulses within GRBs became broader during the course of a burst, as would be expected in the simplest external shock models. On the other hand, Tan et al. (2001) noted the actual GRB lightcurve variability timescale for many bursts, particularly those with identified afterglows, was much longer ($\sim$ several seconds) than the canonical value

($\sim$ tens of milliseconds) often considered: in other words most of gamma-ray energy is liberated in relatively long duration temporal features.

In both of the above scenarios, the afterglow emission comes from external shocks, but the properties of this emission depend on the Lorentz factor, magnetization and density of the ejecta, as well as the density of the ambient medium (Mészáros & Rees 1997). These could have quite different typical values depending on the progenitor model, perhaps leading to large variations in the ratio of gamma-ray to afterglow luminosity.

In addition to models involving supernovae/hypernovae, there are other models of GRB progenitors, such as neutron star mergers, that may contribute to the observed GRB population. Again, it would seem to be a great coincidence if these models and those produced from the core collapse of a massive star had indistinguishable variability and afterglow properties.

Long GRBs do show quite a wide variety in the properties of their longer-wavelength afterglows. While most long GRBs ($\sim 90\%$) produce X-ray afterglows, De Pasquale et al. (2003) concluded that only about half have "bright" optical afterglows; the remainder have been dubbed "dark" GRBs. The distinction between "bright" and "dark" in this context is not clear-cut: a number of authors have argued that "dark" bursts are on average at least 2 mag fainter in the R band (Ghisellini, Lazzati, & Covino 2000; Reichart & Yost 2001; Lazzati et al. 2002). This is consistent with results from the HETE2 satellite that suggest afterglows are actually present following most bursts, but have a wide range of intrinsic luminosities (Lamb et al. 2004). In the radio, Frail et al. (2003) found that 25 out of 75 GRBs had *detected* afterglows.

The faintness of afterglows may have a number of explanations. In the optical it could be due to extinction by dust, absorption by the Lyα forest if the bursts are at high redshift, or due to the afterglow being intrinsically faint due to particular properties of the relativistic ejecta and ambient density. De Pasquale et al. (2003) did not observe the expected soft X-ray absorption that would be present if obscuration is important in most of their sample of dark bursts. If there are "radio-dark" GRBs then this property must be intrinsic to the burst.

The goal of this study is to quantify GRB variability and compare a sample of A-GRBs, (i.e. GRBs with relatively bright afterglow emission corresponding to being in the upper $\sim 1/2$ of their afterglow luminosity functions), with a larger, inclusive "main" sample of bursts, selected only because they are quite bright in gamma-rays and of relatively long duration. To reduce the effects of observations with different instruments we restrict our attention to GRBs with BATSE data.

Given the state of theoretical modeling, it is unclear *a priori* whether afterglow emission strength will correlate with particular variability properties. However, as discussed above, the existence of such a correlation would not be too surprising. If we find that A-GRBs have statistically distinguishable variability properties compared to the main sample, then this is evidence for intrinsic variations in the progenitor model that affect both the gamma-ray emission and the subsequent afterglow. The variation could take the form of a smooth continuum of progenitor properties or of distinct sub-classes. If no difference is seen then either there is only one type of progenitor, or the different types do not lead to correlated variations in afterglow variability and afterglow properties.

Table 1
Afterglow-GRBs observed by BATSE

GRB no.	BATSE trig. no.	Redshift	$C_{\rm peak}$(cts/64ms)	$A_1/A_{\rm tot}$	$(A_1/A_{\rm tot})_0$
GRB 970508	6225	0.8349	172	0.0225	0.0285
GRB 970828	6350	0.9578	1640	0.0148	0.0155
GRB 971214	6533	3.42	404	0.0254	n/a
GRB 980425	6707	0.0085	176	0.00843	0.00845
GRB 980703	6891	0.9662	396	0.0111	0.0107
GRB 990123	7343	1.6004	2990	0.00566	0.00972
GRB 990506	7549	1.3066	3490	0.0167	0.0243
GRB 990510	7560	1.6187	2010	0.0254	0.0357
GRB 991216	7906	1.02	13800	0.0224	0.0215
GRB 000131	7975	4.511	1620	0.0227	0.0355

2. MEASURES OF GRB VARIABILITY

We shall use the structure function to characterize GRB lightcurve variability. First we review other statistical measures of variability that have been employed in GRB studies. We then motivate our choice of the structure function.

Beloborodov, Stern, & Svensson (2000; hereafter BSS) studied the power density spectra (PDS), $P_f = F_f F_f^*$ where F_f is the Fourier transform of the peak-normalized lightcurve, $F(t)$, of BATSE GRBs. Their sample of about 500 bursts was defined by requiring that T_{90}, the time to accumulate from 5% to 95% of the total fluence in the 4 BATSE energy channels was greater than 20 s, that the peak count rate in channels 2+3 (55-110 and 110-320 keV) was > 100 counts per 0.064 s time bin, and that the total fluence was greater than 32 times that of the peak time bin. They concluded the PDS of bursts was well-described by a power law, $P_f \propto f^{-5/3}$ for $f < 1$ Hz. They also found evidence for a break in the power law at higher frequencies, such that the PDS declined more rapidly. The PDS method based on the Fourier transform has disadvantages because GRBs are aperiodic and transient signals, with varying durations. To adjust the PDS of each burst to a uniform frequency range, BSS added artificial zero flux portions to the lightcurve so that the total duration was 1048 s. As they comment, this "zero padding" introduces an artificial, fluctuating contribution to the PDS that can dominate the true signal at low frequencies.

Shen & Song (2003) analyzed the variability of a similar sample of bright, long-duration GRBs by calculating the variation power defined as $P(\tau) = (1/N)\Sigma_{i=1}^{N}(m_i - \bar{m})^2/\tau^2$, where m_i, $i = 1, ..., N$ is a counting series obtained from the time history of the observed photons with a time step τ, including background photons. The power density is calculated via $p(\tau) = P(\tau_1) - P(\tau_2)/(\tau_2 - \tau_1)$. The power density was calculated for a noise series for each burst and then subtracted from $p(\tau)$. Shen & Song found the timescale at which p was a maximum for each burst and claimed evidence for a bimodal distribution in these peak timescales, with roughly half the bursts peaking at $\tau < 1$ s and half peaking at $\tau > 1$ s. We performed this method of analysis on a similar sample of BATSE GRBs (our main sample), finding there were a significant number of bursts where the peak of $p(\tau)$ was at the minimum timescale set by the BATSE time resolution of 64 ms. Also many bursts had a relatively broad and flat-peaked power density, which is not reflected in the single value of the timescale of the peak. For these reasons we have preferred to use our structure function analysis, described below.

Borgonovo (2004) studied the discrete autocorrelation function (ACF, the Fourier transform of the PDS), defined as $A(\tau = k\Delta T) = \Sigma_{i=0}^{N-1} c_i c_{i+k}/A_0$, $k = 1, ..., N-1$, where c_i is the number of counts in a given time bin after subtraction of background b_i and $A_0 \equiv \Sigma_{i=0}^{N-1} c_i^2 - (c_i + b_i)$, of a sample of GRBs with optical afterglows and known redshifts, focusing mainly on those with BATSE data (as in our A-GRB sample). He considered the half width at half maximum of the ACF (corrected for cosmic redshift), claiming evidence for a bimodality in the distribution. However, differences in this width of the ACF depend quite sensitively on the finite duration of the bursts, which are influenced by observational selection effects, and less sensitively on the actual variability properties at a fixed timescale.

Reichart et al. (2001) studied the variability of bursts with known redshifts by looking at the (mean summed squared) difference between the observed lightcurve and the same lightcurve smoothed on a particular timescale, proportional to the burst duration. Using 11 bursts with measured variabilities and isotropic peak luminosities, the value of the smoothing timescale was optimized to give the largest change in isotropic peak luminosity for a given change in variability. By this method a significant correlation between this measure of variability and luminosity was found. One important feature of this method is the use of smoothing timescales that are proportional to burst duration rather than a fixed timescale. Reichart et al. (2001) noted that if fixed timescales were used then no correlation was found.

GRB lightcurves have also been studied by decomposition into pulses of a particular functional form (e.g. Norris et al. 1996; Ramirez-Ruiz & Fenimore 2000; Lee, Bloom & Petrosian 2000; Nakar & Piran 2002; Quilligan et al. 2003). This method suffers because it requires an arbitrary specification of the functional form of the pulses, but has the advantage that once this assumption has been made, relatively good statistics on pulse properties can be obtained from a given set of burst data. Ramirez-Ruiz & Fenimore (2000) looked at pulse width evolution within GRBs finding that pulses did not appear to get broader over the course of bursts, contrary to the simplest models of production in external shocks. Lee et al. (2000) found that pulse timescales tend to be shorter in GRBs with higher peak fluxes, as expected from cosmic time dilation, although there is also tentative evidence for a contribution from processes intrinsic to the bursts.

2.1. *The Structure Function Analysis*

We use the first-order structure function (Rutman 1978), defined as

$$D^1(\tau) \equiv \langle [F(t) - F(t+\tau)]^2 \rangle, \tag{1}$$

where the angular brackets denote an ensemble average, $F(t)$ is the flux at time t and τ is the time lag. For a stationary random process $D^1(\tau) = 2\sigma^2[1 - \rho(\tau)]$, where σ^2 is the variance and $\rho(\tau)$ is the autocorrelation function. Although this is only approximately valid for GRBs, to first order we expect that at short τ, D^1 tends to a constant value that is twice the variance of the measurement noise (i.e. if there were no noise it would tend to zero). For τ longer than the longest correlation time scale, D^1 tends to a value equal to twice the variance of the fluctuation. However, the burst nature of GRBs means that the longest correlation time scale is half the burst duration. For example, for a burst that is 64 s long, the largest value of τ considered is 32 s. As the time bin is 64 ms, there are 1000 flux measurements and $D^1(\tau = 32\,\mathrm{s})$ is based on an average of 500 correlations. $D^1(\tau = 64\,\mathrm{ms})$ is based on an average of 999 correlations.

We take the sample of GRBs selected by BSS as the basis of our main sample. We do not impose the fluence condition (see above) that BSS implemented that affects about 5% of their sample. We do exclude some GRBs lacking good background estimates or full coverage at 64 ms resolution. Our main sample contains 450 bursts. Note that the BSS

sample does not include any bursts detected after 17th June 1998. The A-GRB sample (see Table 1) is made up of 10 bursts with BATSE data and for which afterglow counterparts have been detected. The ability to detect afterglows was developed relatively late in the BATSE mission. Three of the bursts (with trigger nos. 6225, 6533 and 6707) are in both samples, but all of the A-GRBs meet the flux requirements of the main sample.

To define GRB lightcurves from the BATSE data we sum the counts in channels 2 and 3, corresponding to an energy range of ∼55-320 keV, as in the study of BSS. We subtract a background, utilizing published background fits[1] and then normalize the lightcurves so that the amplitude at peak is unity (BSS). The start of each burst is defined by the BATSE trigger time. We define the end of the burst by working backwards from the end of the available data stream to the point when the flux (measured in a single bin) is 5% of its peak value and when the absolute flux (average over 1 s) is $\geq 300\,\mathrm{cts\,s^{-1}}$. The latter condition was imposed to avoid the effects of Poisson fluctuations in noisy bursts. We then set the end of the burst so that the length of the burst is 20% longer than this interval. If the burst duration is still less than 50 s, then we extend the end of the burst to 50 s after the trigger time. Note that for inclusion in our sample the bursts must have $T_{90} > 20$ s, evaluated over all energy channels (BSS). We evaluate $D^1(\tau)$ for each burst. As the time resolution of the data is 0.064 s, the range of τ is thus 0.064 s to at least 25 s.

We then define a sample of noise of the same duration and normalization for each burst by using the data following the above interval. We take the structure function of the noise and subtract this from the structure function of the burst to derive the "noise-subtracted" structure function, $D^1_{\rm ns}$. This procedure is illustrated in Figure 1. The noise-subtracted structure function does not tend to exhibit the plateau at small τ. Discreteness associated with the 64 ms time resolution of BATSE is evident.

In Figure 2a we show the noise-subtracted structure functions for the 10 A-GRBs together with the median and 68 percentile bounds (evaluated at each value of τ) of the distribution of same functions of the main sample.

The slope of the median of the structure functions of the main sample changes fairly abruptly at $\tau \simeq 1-2$ s. This is a similar timescale to the break in the power density spectra reported by BSS. As these authors note, if this signal is produced in the rest frame of a relativistic outflow, then one would expect variations of the outflow Lorentz factor, Γ, to smear out the break. They estimate that the dispersion in Γ would need to be $\Delta\Gamma/\Gamma \lesssim 2$ to preserve the observed break, but regard such a narrow dispersion as being unlikely. Alternatively, BSS comment that the break timescale could be associated with the central engine. However, $1-2$ s is orders of magnitude longer than the dynamical timescale of the central engine (presuming it is a stellar mass black hole). Finally BSS comment that the break timescale may be associated with the observed dynamical timescale of the region where the outflow becomes optically thin, i.e. at the photospheric radius, R_p. Variability on timescales shorter than $t_p = R_p/(c\Gamma^2)$ is suppressed. Again, it appears that a narrow range of Γ would be needed to preserve the sharpness of the break. The same issue applies to a model of generating variability from interaction of the outflow with density inhomogeneities in a wind beyond R_p. Further study, preferably with larger samples, is needed to confirm whether there is indeed a characteristic observer-frame variability timescale of $1-2$ s. Such a timescale would be a challenging constraint on progenitor models.

The redshifts of the A-GRBs are known so we can correct for cosmological time dilation (Fig. 2b). Note, however, that this analysis does not account for the use of a fixed observed energy range, ∼55-320 keV, to define the lightcurves. The variability properties of lightcurves are likely to depend on the rest frame energy of the emission. To examine this issue, we considered the structure functions of main sample burst light curves defined with observed energies 25-110 keV (channels 1+2) and >110 keV (channels 3+4) (Fig. 2c). We find that bursts have relatively more short (sub-second) timescale variability at higher energies than at lower. This is consistent with the results of Fenimore et al. (1995), who studied the dependence of autocorrelation function width with observed energy for 45 bright GRBs observed by BATSE and found it to be $\propto E^{-0.4}$.

In order to characterize the relative amounts of power on short and long timescales we consider the area under the structure function for $0.1 < \tau < 10$ s. All the bursts in our samples have a well-defined value of $D^1_{\rm ns}(\tau)$ over this regime. As a very simple measure of relative variability, we consider the ratio of $A_1 \equiv \int_{0.1\,{\rm s}}^{1\,{\rm s}} D^1_{\rm ns}(\tau)\,d\tau$ to $A_{\rm tot} \equiv \int_{0.1\,{\rm s}}^{10\,{\rm s}} D^1_{\rm ns}(\tau)\,d\tau$. For most of the afterglow sample we can also determine the corresponding area ratio for $D^1_{\rm ns}(\tau_0)$ (this is not possible only for GRB 971214, a relatively short burst at high redshift). The uncertainties in $A_1/A_{\rm tot}$ are largest for noisy bursts that have a relatively small value of A_1, the value of which is quite strongly influenced by the noise subtraction.

Given the trends in variability with observed energy, as determined from the large main sample (Fig. 2c), we expect that higher-redshift bursts in the A-GRB sample, which are being observed at higher rest-frame energies, should exhibit shorter variability timescales and have relatively more power on shorter timescales. We show the dependence of the rest frame area ratio with $1+z$ in Fig. 3. There is an apparent weak correlation of increased sub-second variability with $1+z$, but this effect is dominated by the lowest and highest redshift bursts in the sample. At any redshift, we expect quite a broad distribution in $(A_1/A_{\rm tot})_0$, so a larger sample is required before one can look for a statistically significant correlation, particularly as GRB 980425 may be very different in nature from the other bursts (e.g. because of its small γ-ray luminosity, Galama et al. 1998).

The distributions of $A_1/A_{\rm tot}$ are shown in Figure 4 for the A-GRB and main samples (see also Table 1 for the A-GRBs). We performed a Kolmogorov-Smirnov (KS) test on these two data sets. This yielded a probability of 0.030 that they are drawn from the same distribution. The sense of the discrepancy can be seen from Figure 4: there are no A-GRBs with relatively high values of $A_1/A_{\rm tot}$, i.e. they are relatively lacking in sub-second scale power. This result agrees with the

[1] http://cossc.gsfc.nasa.gov/batseburst/sixtyfour_ms/bckgnd_fits.html

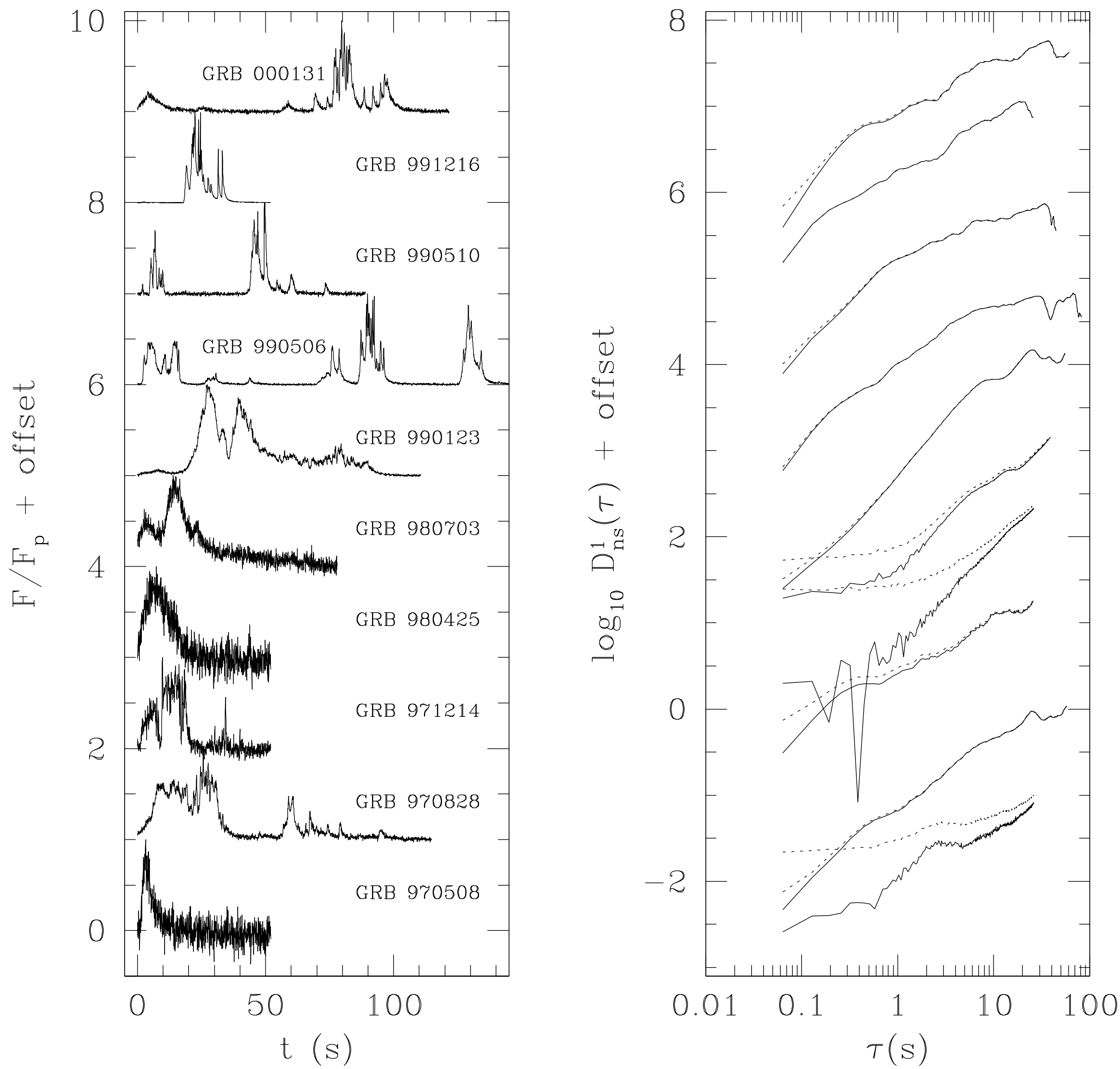

Fig. 1.— Left panel: BATSE light curves (peak-normalized, channels 2+3, offsets $0, +1, ..., +9$) of the A-GRB sample (the final ~ 20 s of GRB 990506 are not shown). (b) Right panel: Noise-subtracted structure functions, $D^1_{\rm ns}(\tau)$ (solid lines) of the same bursts (offsets $0, +1, ..., +9$). We show the structure functions before noise subtraction with dotted lines.

qualitative assertion by Tan et al. (2001) that "most of the GRBs with afterglows have relatively smooth pulses".

The formal probability of 0.030 that the A-GRB and main samples can be drawn from the same distribution is small, but not negligible. Several factors make it relatively difficult to pick out a distinct population of "dark" GRBs, i.e. GRBs with faint afterglows, even if one is present in the main sample: the main and A-GRB distributions of $A_1/A_{\rm tot}$ are quite broad; the samples overlap, so that the main sample probably contains a significant fraction of bursts that do create optical afterglows (this is also implied by the results of De Pasquale et al. 2003 and Lamb et al. 2004); the A-GRB sample is small; there may be differences introduced if the A-GRB and main samples have significantly different redshift distributions (we are forced to assume that these are the same so that the effects of cosmic time dilation and the dependence of variability on rest frame energy are averaged out). The test could obviously be improved if the samples (particularly of A-GRBs)

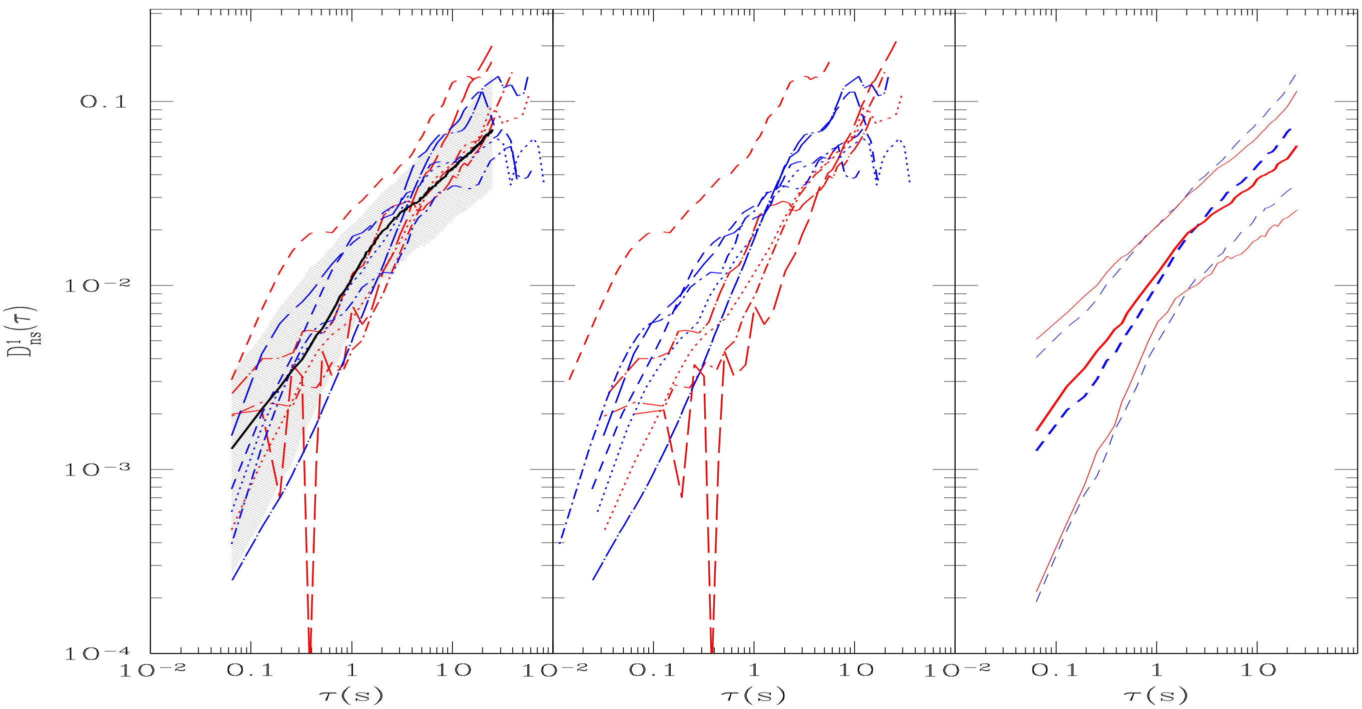

FIG. 2.— (a) Left panel: Noise-subtracted structure functions, $D^1_{\rm ns}(\tau)$, for the A-GRB sample (various non-solid line types). The median of the main sample is shown by the heavy, solid line, and the interval containing 68% of this sample is shown by the shaded region. (b) Middle panel: the same as (a), but now only showing the A-GRBs corrected for redshifting of the variability timescales. (c) Right panel: the same as (a), but now comparing the main sample at lower (25-110 keV; channels 1+2 — dashed heavy line is the median and the upper and lower thin dashed lines delineate 68% of the sample) and higher (>110 keV; channels 3+4 — equivalent red solid lines) observed energies. At higher energies the GRBs have relatively more sub-second scale variability.

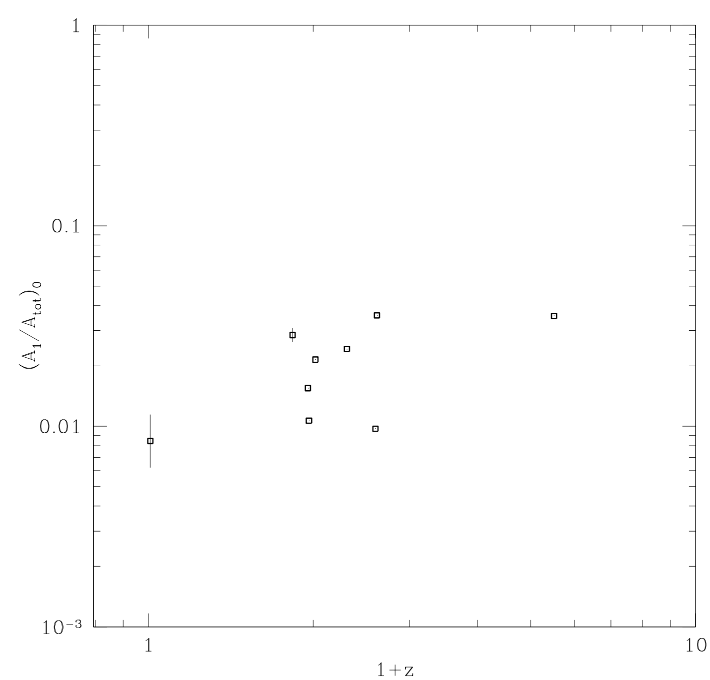

FIG. 3.— The dependence of rest frame area ratio, $(A_1/A_{\rm tot})_0$, of structure functions of A-GRBs with $1+z$, or equivalently the rest frame energy that is probed by the BATSE observations. For those bursts with sufficient post-burst data to create more than one noise sample, the error bars indicate the uncertainty introduced by the noise subtraction. These are only significant for GRB 980425 and GRB 970508.

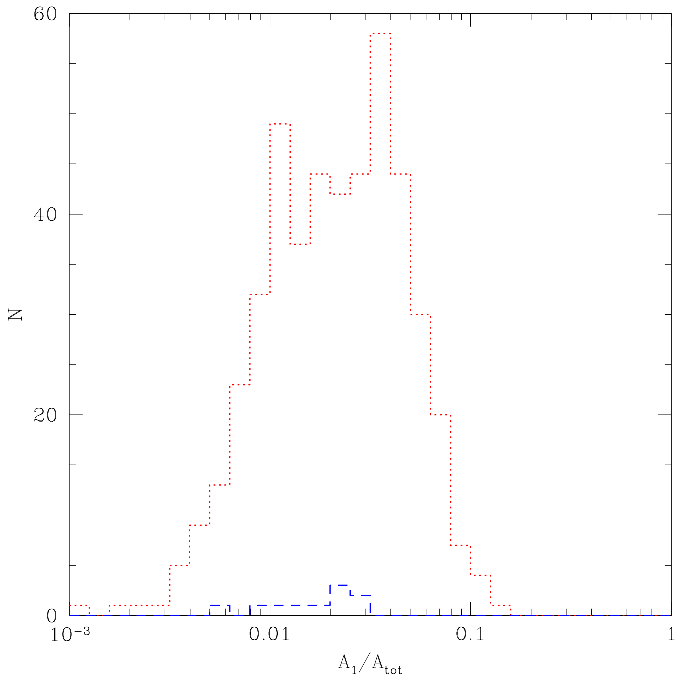

Fig. 4.— Histograms of area ratio $A_1/A_{\rm tot}$ of structure functions from A-GRB (dashed) and main (dotted) samples.

were larger. Although about 20 additional A-GRBs have been observed with instruments other than BATSE, many of these bursts have lower signal-to-noise because of the smaller effective areas of the other instruments. Additionally, not all the data are publicly available at present. In restricting our analysis to only the BATSE sample we also circumvent problems due to different instrumental selection effects between the A-GRB and main samples.

Is the apparent discrepancy between the A-GRB and main samples an artifact of the particular method of comparison? The area ratio $A_1/A_{\rm tot}$ is a particularly simple way of measuring relative variability over these timescales. We have also repeated the analysis for ratios of the areas defined from 0.2 to 2 s and 0.2 to 20 s. The probability of a single parent distribution remains small at 0.029, but this is obviously not a completely independent test. Although the structure functions are not particularly well approximated by single power laws, we have found the best fitting indices for each burst (weighting the structure function uniformly in $\log \tau$) and compared these distributions. We find that they are not significantly different. This illustrates the difficulty of trying to characterize the variability properties of bursts with a single number.

In order to gain more insight into the nature of variability differences that are indicated by the $A_1/A_{\rm tot}$ statistic, in Figure 5 we show the lightcurves and structure functions of the ten bursts with the lowest and highest values of $A_1/A_{\rm tot}$ from the main sample. The bursts with the smallest value of the area ratio (i.e. those with relatively less 0.1 s to 1.0 s scale variability) indeed appear to be very "smooth" (remember that variation due to noise fluctuations has been subtracted off the structure functions). There is only one case out of ten (Trigger no. 5723) where this does not appear to be the case and the burst is in fact dominated by quite short timescale features. The low area ratio of this burst is probably due to an uncertain and large correction for the variability due to noise.

Now consider bursts with the largest values of the area ratio: nine out of ten exhibit a single, very strong, short-timescale initial pulse (which sets the peak normalization), followed by relatively minor emission features. This shows that the $A_1/A_{\rm tot}$ statistic is working to separate GRBs with different relative amounts of sub-second timescale variability. Also since the morphologies of the bursts with the largest values of $A_1/A_{\rm tot}$ are quite homogeneous as a group, forming quite a distinct subset of the range of morphologies exhibited by long-duration GRBs, it is possible that this is caused by real physical differences in their progenitors. Such differences may also explain why none of the A-GRBs, i.e. "bright-afterglow" GRBs, populate this region of $A_1/A_{\rm tot}$ parameter space or exhibit this morphology. We note that some of these bursts, if observed with lower signal to noise, might be classified as short-duration bursts, i.e. with $T_{90} \lesssim 2$ s. This interpretation is consistent with the finding that short-duration GRBs do in fact have faint, longer-duration hard x-ray tails (Lazzati, Ramirez-Ruiz, & Ghisellini 2001), as seen by co-adding a large number of short bursts. Another partial explanation for the lack of detected afterglows from these types of bursts may then be instrumental, as the localizations of short bursts by previous and current satellites have been relatively poor compared to longer bursts.

What are the lightcurve and variability properties of the "dark" GRBs, as identified by De Pasquale et al. (2003)? First note that many of these bursts may be optically dark in their afterglows because they are faint in all their emission properties: De Pasquale et al. find the X-ray fluxes of A-GRBs are about 5 times higher than the dark bursts — if the optical-to-X-ray fluxes are constant then 75% of the dark bursts have predicted optical fluxes below the level to which

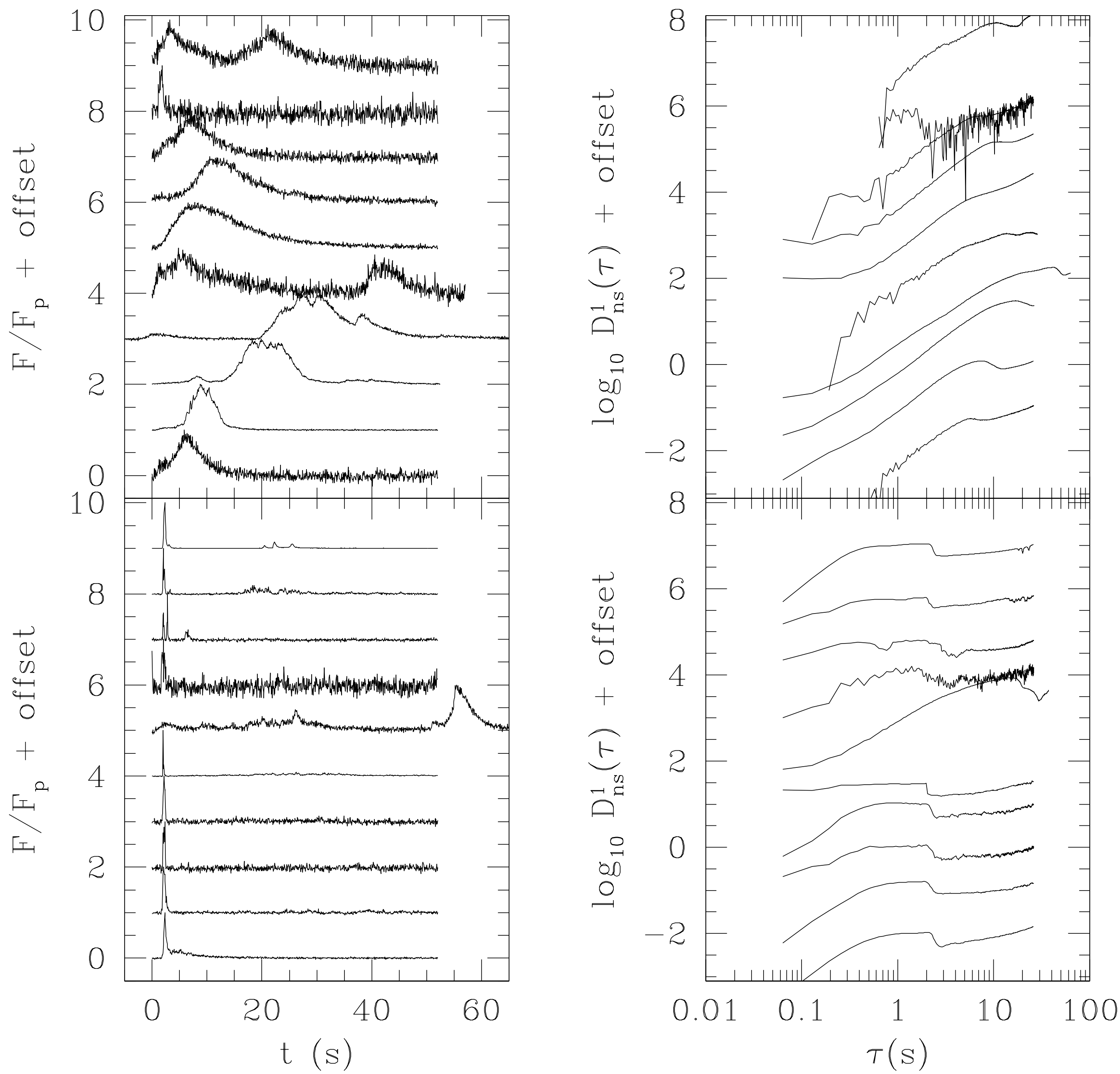

Fig. 5.— Peak-normalized lightcurves (left panels, with offsets $0, +1, ..., +9$) of samples of GRBs with the minimum (top panel: BATSE trigger nos. 1039, 1886, 2067, 2138 (shifted also by +50 s so first weak pulse is not shown), 2276, 2387, 3003, 5531, 5723, 6167) and maximum (bottom panel: BATSE trigger nos. 0467, 0503, 1546, 1626, 1997, 2700, 3248, 5572, 5725, 5989) area ratios $A_1/A_{\rm tot}$ of their structure functions (displayed in the right panels with offsets of $0, +1, ..., +9$).

they were observed. Conversely, about 25% of the dark bursts have optical-to-X-ray flux ratios that are at least 4-10 times smaller than the A-GRBs. A lack of soft X-ray absorption suggests that this faintness is not due to obscuration. The γ-ray and hard X-ray light curves of the dark bursts listed by De Pasquale et al. (2003) are very diverse, including both short ($\sim$ few seconds) and long ($\sim$ hundreds of seconds) bursts. Of the 20 dark bursts, four were observed by BATSE: GRBs 970111, 971227, 990907, 991014 (with BATSE trigger nos. 5773, 6546, 7755, 7803). The data for GRB 990907 are not available in the current BATSE catalogue. GRB 970111 is a relatively smooth burst with multiple peaks and a 50 s duration, while the remaining two bursts are quite short ($\sim 5-10$ s) with peaks with rise and fall timescales $\lesssim 1$ s. Thus some of the lightcurves and variability properties of the dark bursts are similar to the sample shown in the lower panel of

Figure 5, but some are not, as is to be expected given the different reasons why GRBs may be classified as optically dark.

3. CONCLUSIONS

After reviewing methods of assessing GRB variability, we have presented tentative evidence that the variability properties, as measured by the structure function, of A-GRBs, i.e. bursts with detected afterglows, differ from the more general population of long-duration GRBs. The A-GRBs have relatively little sub-second variability. This may be because the wider sample of GRBs contains a significant number of "dark" bursts, i.e. with relatively faint afterglows, that have a different physical origin and relatively more shorter timescale (< 1 s) variability. It is also possible that our result is explained by a more continuous trend from a single progenitor model causing GRBs with brighter afterglows to have less short timescale variability.

If the dark bursts were simply at higher redshifts then the above effect might be due to the fact that we observe the bursts at a higher rest frame energy, where variability timescales are shorter (Fig. 2c). However, cosmic time dilation would tend to counteract this effect. Furthermore, the example lightcurve morphologies shown in Figure 5 are suggestive that there are different physical mechanisms involved as the variability, as measured by the $A_1/A_{\rm tot}$ statistic, changes.

To further test the above hypothesis, we need more stringent constraints on the afterglow to γ-ray flux ratios of the bursts with relatively high short timescale variability, such as those shown in the lower panel of Figure 5. This should be possible with the *Swift* satellite.

In §1 we argued that there are good physical reasons to expect different classes of GRBs, depending on how long the forming black hole can power relativistic jets and how long it takes these jets to burrow through the stellar envelope. There are of course many other theoretical models that may produce some of the observed GRBs, such as the mergers of neutron stars. More work is needed on the expected variability and afterglow properties of these models.

We thank B. Draine, C. Matzner, C, McKee and E. Rossi for helpful discussions, A. Beloborodov for providing a list of the BSS sample of GRBs and Y. Kaneko for helping with the BATSE data extraction for GRBs 970828 and 000131. We also thank the referee for comments that greatly improved the paper. This work was supported in part by NASA grant NAG5-10811. JCT has received support via a Spitzer-Cotsen Fellowship from the Department of Astrophysical Sciences and the Society of Fellows in the Liberal Arts of Princeton University, and via a Zwicky Fellowship from the Inst. of Astronomy, ETH Zürich.

REFERENCES

Aloy, M. A., Müller, E., Ibanez, J. M., Martí, J. M., & MacFadyen, A. 2000, ApJ, 531, L122
Beloborodov, A. M., Stern, B. E., & Svensson, R. 2000, ApJ, 535, 158
Bloom, J. S., Kulkarni, S. R., & Djorgovski, S. G. 2002, AJ, 123, 1111
Borgonovo, L. 2004, A&A, 418, 487
Colgate, S. A. 1974, ApJ, 187, 333
De Pasquale, M., Piro, L., Perna, R. et al. 2003, ApJ, 592, 1018
Dermer, C. D. & Mitman, K. E. 1999, ApJ, 513, L5
Djorgovski, S. G., Bloom, J. S., & Kulkarni, S. R. 2003, ApJ, 591, L13
Djorgovski, S. G., Kulkarni, S. R., Bloom, J. S. et al. 2001, in Gamma-ray Bursts in the Afterglow Era, 218
Fenimore, E. E., Epstein, R. I., & Ho, C. 1993, A&AS, 97, 59
Fenimore, E. E., In't Zand, J. J. M., Norris, J. P., Bonnell, J. T., & Nemiroff, R. J. 1995, ApJ, 448, 101
Frail, D. A., Kulkarni, S. R., Berger, E., & Wieringa, M. H. 2003, AJ, 125, 2299
Galama, T. J., Vreeswijk, P. M., van Paradijs, J. et al. 1998, Nature, 395, 670
Ghisellini, G., Lazzati, D., & Covino, D. 2000, Proceedings of the 2nd Workshop on Gamma-Ray Bursts in the Afterglow Era, Rome, eds. E. Costa, F. Frontera, & Hjorth
Kulkarni, S. R., Berger, E., Bloom, J. S., et al. 2000, in Gamma-ray Bursts, 5th Huntsville Symposium, eds.: R. M. Kippen, R. S. Mallozzi, G. J. Fishman. AIP Conf. Ser., 526. (AIP; New York), 277
Lamb, D. Q., Ricker, G. R., et al. 2004, New Astronomy Reviews, 48, 423
Lee, A., Bloom, E. D., & Petrosian, V. 2000, ApJS, 131, 21
Lazzati, D., Covino, S., & Ghisellini, G. 2002, MNRAS, 330, 583
Lazzati, D., Ramirez-Ruiz, E., & Ghisellini, G. 2001, A&A, 379, L39
Lithwick, Y. & Sari, R. 2001, ApJ, 555, 540
Matzner, C. D. 2003, MNRAS, 345, 575
Matzner, C. D. & McKee, C. F. 1999, ApJ, 510, 379
Mészáros, P. & Rees, M. J. 1997, ApJ, 476, 232
Nakar, E., & Piran, T. 2002, MNRAS, 331, 40
Norris, J. P. et al. 1996, ApJ, 459, 393
Piran, T. 1999, Phys. Rep., 314, 575
Proga, D., MacFadyen, A. I., Armitage, P. J. & Begelman, M. 2003, ApJ, 599, L5
Quilligan, F., McBreen, B., Hanlon, L, McBreen, S., Hurley, K. J., & Watson, D. 2002, A&A, 385, 377
Ramirez-Ruiz, E., & Fenimore, E. E. 2000, ApJ, 539, 712
Reichart, D. E., Lamb, D. Q., Fenimore, E. E., Ramirez-Ruiz, E., Cline, T. L., & Hurley, K. 2001, ApJ, 552, 57
Reichart, D. E., & Yost, S. A. 2001, ApJ, submitted (astro-ph/0107545)
Rutman, J. 1978, Proc. IEEE, 66, 1048
Shen, R. F. & Song, L. M. 2003, PASJ, 55, 345
Stanek, K. Z., Matheson, T., Garnavich, P. M., et al. 2003, ApJ, 591, L17
Tan, J. C., Matzner, C. D., & McKee, C. F. 2001, ApJ, 551, 946
Woods, E. & Loeb, A. 1995, ApJ, 453, 583
Zhang, W., Woosley, S. E. & MacFadyen, A. I. ApJ, 586, 356